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14. ABSTRACT This paper reviews recent world-wide progress in silicon-based photonics-and optoelectronics in order to provide a context for the papers in this special section of the IEICE Transactions. The impact of present and potential applications is discussed.					
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# The Impact of Silicon Photonics

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**SUMMARY** This paper reviews recent world-wide progress in silicon-based photonics-and-optoelectronics in order to provide a context for the papers in this special section of the IEICE Transactions. The impact of present and potential applications is discussed.

**key words:** silicon, optoelectronics, integrated photonics

## 1. Introduction

Silicon photonics is presently a “hot topic” of research and development in Asia, Europe and North America—where discoveries in silicon-based photonic science-and-technology are being made at an increased pace due to ramped-up R&D investment by governments, industry and academia [1], [2]. This special issue reports silicon-photonic advances that have been made in Japan, mainland China, Taiwan, Hong Kong and Singapore.

Silicon-based photonic integrated circuits are important in their own right, but the main driver today of the Si photonics field is the quest for low-cost large-scale-integrated Si-based optoelectronic integrated circuits (OEICs)—also known as electronic-photonic integrated circuits (EPICs)—that will be manufactured in state-of-the-art high-volume silicon CMOS foundries (silicon fabs). Potentially, these OEICs have vast and highly significant applications, which if implemented, would make Si optoelectronic chips pervasive in our interconnected planet.

The essential role that silicon nanophotonics will play in the future is highlighted in a new 2007 initiative on ultraperformance nanophotonic intra-chip communication (UNIC) sponsored by the US Defense Advanced Research Projects Agency. The goal is to demonstrate low-power, high-bandwidth, low latency intra-chip photonic communication networks designed to enable chip multiprocessors with hundreds or thousands of compute cores to realize extremely high computational efficiency—a goal that embodies the convergence of computation and communication envisioned by Lionel C. Kimerling. The optoelectronic UNIC project poses a major challenge to the technical community because it will require revolutionary rather than evolutionary advances in science, devices, circuits and computing systems.

An important investigation of nano-scale devices was made at the March 19, 20, 2007 workshop on “very large

scale photonic integration” sponsored by the US National Science Foundation and chaired by Ronging Hui, Usha Varney and Thomas Koch. Corporations and universities now engaged in the fledgling optoelectronics industry need a cost-effective way to demonstrate and optimize their individual OE prototype chips. For that reason, the workshop participants discussed whether a government-sponsored national CMOS-photonics User Facility should be set up in the United States to establish a cost-shared “photonics-ready” silicon foundry that will provide application-specific OEIC prototypes for users throughout the technical community. The proposed user fab would rely upon the SOI photonic-component manufacturing “libraries” that are being developed at BAE Systems, Luxtera, and elsewhere.

The basic motivation for optoelectronics (OE) is to attain electronic drivers-and-controllers that are intimately integrated with their laser diodes, modulators, amplifiers and photodetectors. The larger OE goal is to create greatly improved devices, subsystems and systems. Silicon of course is not the only OE medium, and silicon OE is currently struggling with the issue of silicon on-chip light sources. That is why OE based upon III-V semiconductors is likely—in the near term—to give Si OE strong competition in “small-scale” integration situations: for example in 1.55  $\mu\text{m}$  transceivers where III-V lasers and photodetectors can be integrated monolithically on InP. However, two key advantages of silicon appear in the bigger picture: the very low chip costs that high-volume Si OE production will ultimately give, and the very high level of “sophistication” (functionality) that Si OE will eventually provide—derived from hundreds or thousands of photonic components integrated on-chip with perhaps a million transistors. The possible Si OE applications areas are: (1) optical interconnects at cabinet-level, board-level and within a chip, (2) sensor technologies for the near-, mid-, and far-infrared [3]–[5], (3) signal processing functions, (4) imaging, (5) displays, (6) energy conversion, (7) illumination and (8) gaming.

If I look inside these eight categories, I can identify specific cases in which “well developed” OEICs would make a major impact upon global society and commerce. They are: (1a) fast fiber-optic transceivers for datacomm and telecomm, (1b) switched communication networks, (2a) infrared spectrometer-on-a-chip, (2b) photonic laboratory-on-a-chip for sensing chemical and biological agents, (2c) lab-on-a-chip for environmental monitoring, (2d) medical diagnosis lab, (3a) wireless mobile multi-function “phone-like” device, (3b) optical time-delay beam-steerer for a phased-

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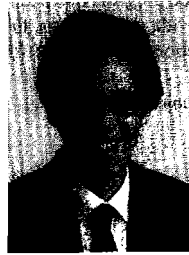
array microwave antenna, (3c) RF-optical receivers for RF spectrum analysis, (3d) ultrafast analog-to-digital converters, (3e) reconfigurable wavelength-division multiplexers and demultiplexers, (3f) reconfigurable optical filters, (3g) electronic warfare processors, (3f) photonically enhanced microwave and millimeter-wave circuits, (3h) optical buffer memories, (3i) electrooptical logic that operates on phase-coherent light beams, (3j) photonic tester of electronic ICs, (3k) bionic signal processors, (3l) neural network processors, (3m) data-fusion chips using inputs from several sensors, (4a) focal-plane imager array with integral readout, (4b) infrared-to-visible image converter chip, (5) chip-scale electrooptical display with integral scanning, (6) highly efficient group IV photovoltaic solar cells with integral signal processing, (7) efficient group IV solid-state lighting devices, (8) ultrafast playstation computer chips. These are the challenges and opportunities for those of us involved in Si OE.

Some of the cutting-edge research topics in Si photonics are nanophotonics, plasmonics, photonic crystals, nanomembranes, SiGeSn alloys, commercial manufacturing methods, nonlinear optics, NEMs and microfluidics. The papers presented at the IEEE LEOS 4th International Conference on Group IV Photonics (Tokyo, September 19–21 2007) give a good indication of the present R&D thrusts of silicon photonics. The sessions there deal with the Japanese MARAI optical interconnection project, waveguides and filters, OE and III-V hybrid integration, MEMs and 3D structures, modulators and switches, disruptive materials and process technologies, nonlinear optics and active functions, slow-light devices and passive photonic crystals, light-source materials, light-source devices and structures, and detectors.

The papers here reflect these GFP themes. In this special issue of the IEICE Journal, important results are presented on chip-scale photonic-integration, two-ring microresonator filters, Si nanocrystal-based LEDs, high-performance microresonator devices, nonlinear optical devices, hybrid integration of active GaPN/InGaPN devices for OEICs, on-chip optical interconnection, Si-based light emitting materials and devices, and mesa-type Ge-on-Si photodetectors. These are fine contributions to Si OE. Further work on novel materials, structures, devices and manufacturing techniques by scientists in Asia (and elsewhere worldwide) will make the vision of commercial Si OE a reality.

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**Richard Soref** received the Ph.D. degree in electrical engineering from Stanford University in 1963. During 1964–1965, he was a Staff Member at MIT Lincoln Laboratory. From 1965 to 1983, he was a Staff Member at the Sperry Research Center. In 1983, he joined the U.S. Air Force Research Laboratory, Hanscom AFB, where he is currently a Research Scientist in the Sensors Directorate. During his 43-year career in photonics research, he has investigated liquid-crystal devices, nonlinear optics, electro-optical

switching, optical waveguide components, ferroelectric-crystal modulators, semiconductor field effects, quantum well devices, band theory and related topics. He is best known for developing and advocating the field of silicon-based photonics-and-optoelectronics. Dr. Soref holds 51 US patents, has published seven book chapters, and has authored or co-authored over 190 peer-reviewed papers. He has given numerous invited lectures and conference presentations. He has been active in the conference committees of the Optical Society of America (OSA), Materials Research Society (MRS) and the Lasers-and-Electro-Optics Society (LEOS). In 2004, he founded the IEEE-LEOS 1st International Conference on Group IV Photonics. Richard is a Life Fellow of the IEEE and a Fellow of OSA, Air Force Research Laboratory, and the Institute of Physics UK.